The Gamma-Ray Spectrum of the Sun

Joseph F. Dolan
Astronomy Department, Harvard University, Cambridge, Massachusetts,
and N A S A Institute for Space Studies, New York, New York

and

G. G. Fazio
Smithsonian Astrophysical Observatory
and Harvard College Observatory, Cambridge, Massachusetts

Abstract. We investigate mechanisms for the production of gamma radiation ($h\nu > 10$ kev) by the sun and predict fluxes at the earth. The gamma radiation emitted by the quiet sun is negligible compared to emission during a solar flare. The most important emission mechanism in the 10 kev to 1 Mev energy region is bremsstrahlung by flare-accelerated electrons. The photon spectrum is continuous and decreases monotonically with energy. Flare-accelerated protons will interact with carbon, nitrogen, and oxygen nuclei by inelastic scattering and spallation reactions, producing gamma radiation as a result of nuclear de-excitation. Neutrons resulting from spallation reactions will be partially captured by protons to produce deuterium and 2.23 Mev gamma radiation. The intensity of this line emission is proportional to the neutron density in a flare. Line emission at 0.51 Mev results from positron-electron annihilation. Positrons are produced by beta-decay of radioactive nuclei generated by spallation

over / leaf

[redacted]

reactions and by the decay of π^+ mesons produced in proton-proton reactions. The primary source of photons with energy greater than 50 Mev is the decay of π^0 mesons, which are also produced in proton-proton reactions.

Flux estimates indicate that the detection of gamma radiation resulting from a solar flare is feasible and would yield information on nuclear reactions as well as on the intensity and spectrum of high-energy protons and electrons.

Author

I. Introduction

With the advent of high-altitude balloons, rockets, and satellites, it is now possible to investigate all regions of the electromagnetic spectrum of the sun. One region of particular interest is the extreme high-frequency range, where little work has been done before. In this paper we shall investigate the gamma-ray spectrum emitted by the sun and determine what new information about the sun, and solar flares in particular, we can learn from the detection of this radiation. We shall also investigate the various gamma rays to determine which portion of the spectrum is most feasibly detectable and which yields the most direct information on solar-flare structure.

We shall adopt the definition of gamma radiation as any electromagnetic radiation in which the photon energy ($h\nu$) exceeds 10 kev (1.60×10^{-8} ergs, corresponding to a frequency of 2.42×10^{18} sec^{-1} and a wavelength of 1.24 angstroms).

II. Gamma-ray Production Mechanisms

In general, gamma radiation can be produced by the following mechanisms:

(1) synchrotron radiation

(2) electron recombination with atoms (free-bound transitions)

(3) decay of naturally radioactive nuclei

(4) inverse Compton effect

(5) bremsstrahlung (free-free transitions)

(6) nucleon-nucleon reactions

  (a) thermonuclear reactions

  (b) de-excitation of nuclei produced by nuclear bombardment

  (c) π^0-meson decay

(7) electron-positron annihilation

  (a) beta-decay

  (b) π^+-meson decay

We shall investigate each of the above sources to evaluate the relative intensities and types of spectra produced. To do this, however, we must understand gamma-ray absorption processes on the sun and the physical conditions existing in the quiet sun and in solar flares.

III. Gamma-ray Absorption Mechanisms

Although gamma rays may be absorbed or scattered in many ways by electrons, nucleons, electric fields, and meson fields [Evans, 1955], there are three predominant types of interactions: (1) the photoelectric effect, (2) the Compton effect, and (3) electron-positron pair production. The total absorption cross section (including elastic scattering) for a photon of frequency ν is given by

$$\sigma_\nu = \sigma_{ph} + \sigma_c + \sigma_{pr}, \quad \mathrm{cm}^2 \tag{1}$$

where σ_{ph} is the cross section for the photoelectric effect, σ_c for the Compton effect, and σ_{pr} for pair production. The absorption coefficient, k_ν, is defined by

$$k_\nu = \sigma_\nu N_a \ \mathrm{cm}^{-1} , \tag{2}$$

where N_a is the number of agents per cm^3 with which an interaction can occur. The gamma-ray equivalent to the optical depth of visual radiation is given by

$$t_\nu = \int_x^{x_0} k_\nu \, dx , \tag{3}$$

where x and x_0 are the distances from the center of the sun to the source and to the observer. Thus photons of initial intensity I_0, after traversing a distance $x_0 - x$ of absorber, will have an intensity I, given by

$$I = I_0 e^{-t_\nu} . \tag{4}$$

Photoelectric Effect. To calculate the photoelectric absorption coefficient over the photon energy range of 10 kev to 10 Mev we must use several different formulas. The main features of the absorption, however, are given [Kaplan, 1956] by:

$$\sigma_{ph} = \phi_0 \, Z^5 \left(\frac{1}{137}\right)^4 4\sqrt{2} \left(\frac{M_0c^2}{h\nu}\right)^{\frac{7}{2}} , \qquad \text{cm}^2/\text{atom} \quad (5)$$

where

$$\phi_0 = \frac{8\pi}{3}\left(\frac{e^2}{M_0c^2}\right)^2 = 6.651 \times 10^{-25} \; ; \qquad \text{cm}^2 \quad (6)$$

$h\nu$ is the energy of the incident photon; M_0c^2 is the rest energy of the electron; and Z is the atomic number of the absorbing material. This formula applies only to the ejection of electrons from the K shell of the atom (~ 80 per cent of the photoelectric effect) and assumes that the photon energy is small enough so that we can neglect relativistic effects but is still much larger than the K-shell binding energy. The photoelectric cross sections as a function of energy are given in Table 1.

Compton Effect. The total Compton cross section (elastic scattering and absorption) is given [Evans, 1955] by

$$\sigma_c = \frac{3}{4}\phi_0 \left\{\frac{1+\alpha}{\alpha^2}\left[\frac{2(1+\alpha)}{1+2\alpha} - \frac{1}{\alpha}\ln(1+2\alpha)\right] + \frac{1}{2\alpha}\ln(1+2\alpha) - \frac{1+3d}{(1+2\alpha)^2}\right\} , \qquad \text{cm}^2/\text{electron} \quad (7)$$

where $\alpha = h\nu/M_0c^2$. For $\alpha << 1$,

$$\sigma_c = \phi_0 \, (1 - 2\alpha + 5.2\alpha^2 - 13.3\alpha^3 + \ldots), \qquad \text{cm}^2\text{/electron} \quad (8)$$

and for $\alpha >> 1$

$$\sigma_c = \frac{3}{8}\phi_0 \frac{1}{\alpha} \left[\frac{1}{2} + \ln 2\alpha\right] . \qquad \text{cm}^2\text{/electron} \quad (9)$$

Values of the total Compton cross section are given in Table 2.

Electron-Positron Pair Production. The total pair-production cross section per nucleus is [Evans, 1955]

$$\sigma_{pr} = \sigma_0 Z^2 \int_0^{h\nu - 2M_0c^2} \frac{P \, dT_+}{h\nu - 2M_0c^2} ,$$

$$= \sigma_0 Z^2 \overline{P} , \qquad \text{cm}^2\text{/nucleus} \quad (10)$$

where

$$\sigma_0 = \frac{1}{137}\left(\frac{e^2}{M_0c^2}\right)^2 = 5.80 \times 10^{-28} \quad ; \qquad \text{cm}^2\text{/nucleus} \quad (11)$$

T_+ is the kinetic energy of the positron produced; Z is the atomic number of the absorber; P is a dimensionless quantity that is a complicated function of $h\nu$ and Z, varying between 0 (for $h\nu \leq 2 M_0c^2$) and about 20 (for $h\nu = \infty$) for all values of Z; and $\overline{P}$ is the average value of P . Evans [1955] gives a plot of P as a function of $T_+/(h\nu - 2 M_0c^2)$. Analytical integration of the equation for σ_{pr} is possible only for relativistic cases:

$$\sigma_{pr} = \sigma_0 Z^2 \left(\frac{28}{9} \ln \frac{2h\nu}{M_0c^2} - \frac{218}{27}\right) \quad M_0c^2 << h\nu << 137\, M_0c^2 Z^{-1/3} , \tag{12}$$

$$\sigma_{pr} = \sigma_0 Z^2 \left[\frac{28}{9} \ln (183Z^{-1/3}) - \frac{2}{27}\right] \quad h\nu >> 137\, M_0c^2 Z^{-1/3} . \tag{13}$$

Values of the pair-production cross section are given in Table 3.

To estimate the effect of gamma-ray absorption above the photosphere, we shall adopt a path length in the corona of three times the solar radius and overestimate the average electron density there by assuming it to be 10^9 cm^{-3} over the entire path. Using these values, we have

$$t_\nu = 2.1 \times 10^{20} (\sigma_\nu) . \tag{14}$$

Likewise, if we adopt a density of 3×10^{13} electrons/cm^3 in the flare and a path length in the flare of 10^9 cm, then

$$t_\nu = 3 \times 10^{22} (\sigma_\nu) . \tag{15}$$

The maximum value of σ_ν in the defined gamma-ray energy region occurs at 10 kev. In the corona photoionization is negligible, since only a few nonabundant atoms retain even K-shell electrons. In most of the chromosphere and in the flare itself, the temperature is high enough so that hydrogen and helium are completely ionized. Therefore, at 10 kev

$$\sigma_\nu \approx \sigma_c , \tag{16}$$

and

$$t_\nu = 2.1 \times 10^{20} \sigma_c \cong 10^{-4} \tag{17}$$

for the corona, and

$$t_\nu = 3 \times 10^{22} \sigma_c \cong 10^{-2} \tag{18}$$

for flares. Thus gamma-ray absorption above the photosphere is negligible.

It is interesting to note that at high gamma-ray energies, e.g., greater than 50 Mev, t_ν has its smallest value, and therefore, radiation of this energy produced within a depth of ~ 58 gm/cm^2 from the surface of sun will undergo little absorption.

2

IV. Properties of the Sun and Solar Flares Important to Gamma-Ray Production

Because of the absorption in the interior of the sun, we cannot detect gamma radiation originating at its center. We are therefore predominantly interested in surface reactions that can produce this radiation. We shall find that solar flares are the primary source of gamma radiation. In this section we shall summarize briefly the structure of the sun as related to chromospheric flares and establish a simple approximation to the nature of the interacting region that produces gamma rays.

Typical values of the temperature and density of the chromosphere and corona are given in Table 4 [Thomas and Athay, 1961; de Jager, 1959; Van de Hulst, 1953].

A flare is defined as a sudden, short-lived brightening in H_α of a local region on the sun's disk, occuring in the vicinity of a sunspot. Solar flares are classified according to their area and intensity as seen in the H_α emission line. The approximate area and relative frequency of various types of flares are tabulated in Table 5 [de Jager, 1959; Beckers, 1962]. In the calculations that follow, we shall take the area of a flare as seen against the disk of the sun to be 10^{19} cm^2 . The observed area of a flare is a combination of two areas: the area of the side of the flare as it would be seen on the limb and the area of the top of the flare as seen at the center of the disk. Warwick [1955] has observed the change in measured areas of H_α flares when seen at the center of the disk and at some distance from the center. The result of this work was a height-frequency distribution represented by $e^{-\beta h}$, where $1/\beta = 20,300$ km. For purposes of calculation we shall take the mean thickness of a flare to be 10^9 cm.

The densities in a flare are slightly greater than the densities in the surrounding chromosphere, being of the order of 2 to 3×10^{13} H atoms/cm^3 [de Jager, 1959] . The electron density shall be taken as equal to the proton density. The relative abundances of other elements are given in Table 6 [Goldberg, Müller, and Aller, 1960; Aller, 1958] , where we have assumed normal solar abundance in the flare.

Spectrographic measurements of the kinetic temperatures of flares, as derived from line broadening, give values of the order of 10^5 $^\circ$K [Goldberg, Mohler, and Müller, 1958; Zirin, 1959] . We must point out that these results may be partially caused by mass motions in the line of sight and that the H_α emission observed must come from a region surrounding the high temperature section of the flare, because in the high temperature section hydrogen would be completely ionized.

Magnetic fields of 100 to 200 gauss are observed in plage regions, and their strength may rise to a few thousand gauss in the flare itself [Leighton, 1959].

High-energy particles accelerated and ejected by flares have been observed at the earth. The differential rigidity spectrum of flare protons observed at the earth is given [Freier and Webber, 1963] by

$$\frac{dN'}{dR} = N_0' e^{-R/R_0} , \qquad \text{protons/cm}^2 \text{ sec volt} \quad (19)$$

where R is the rigidity of the proton in volts, and N_0' and R_0 are constants. The rigidity of a particle with momentum p and charge ze is given by

$$R = \frac{pc}{ze} , \quad (20)$$

where c is the velocity of light. When p is in units of ev/c, R in volts is numerically equal to p/z. The kinetic energy, T, of a particle is related to its rigidity by

$$T = \left[z^2 R^2 + (M_0c^2)^2\right]^{\frac{1}{2}} - M_0c^2 \text{ ev} , \quad (21)$$

where M_0c^2 is the rest mass of the particle in electron volts, and R is measured in volts. Values of R_0 and N_0' are given by Freier and Webber for various flares. For protons in the range of 1 Mev to over 2 Bev, the value of R_0 for a given flare was constant but varied from flare to flare from 50 to 300 million volts.

For any given flare the value of R_0 is the same for both protons and alpha particles. The intensity ratio of protons to alpha particles at the same rigidity, p/α, varied from 1 to 50. In the majority of cases this value was one.

High-energy electrons accelerated by a flare have also been observed at the earth [Meyer and Vogt, 1962], but their spectrum and number cannot be determined by the observations.

Because we lack information about the particle rigidity spectrum produced at the sun by a flare, we shall assume an exponential rigidity spectrum for protons and alpha particles with values of R_0 varying from 50 to 300 Mv. We shall also assume that electrons follow an exponential rigidity spectrum, but that the electron rigidity constant, R_0, may be of a different order of magnitude. We shall consider values of R_0 for electrons from 110 Kv to 200 Mv.

It is certainly conceivable that at low energies, e.g., proton kinetic energy less than 30 Mev, an inverse power spectrum of the kinetic energy would produce a better fit to the data. Since we are concerned only with an order-of-magnitude calculation of the gamma-ray flux in this paper, however, we shall assume an exponential rigidity spectrum over all energies.

Estimates of the total number of protons at the sun accelerated by flares vary from 10^{31} to 10^{35} [Hofmann and Winckler, 1963; Peterson and Winckler, 1958, 1959; Friedman, 1963] for protons with energy greater than 10 Mev (R = 136 Mv). The time for these particles to be ejected by the flare may vary from 10 to 1000 seconds. We shall take the total number of protons per second accelerated in flares to be N, where

$$N = N_0 \int_0^\infty e^{-R/R_0}\, dR\ , \qquad \text{protons/sec (22)}$$

$$N = N_0 R_0 = 10^{32}\ . \qquad \text{protons/sec (23)}$$

We shall also assume that the total number of accelerated electrons produced by a flare is equal to the number of accelerated protons produced.

We shall take the ratio of the total number of alpha particles accelerated to the total number of protons accelerated to be the same as the ratio of normal solar abundances, 0.14. We shall neglect the effects of accelerated particles with $Z > 2$.

In order to calculate the gamma-ray production in a flare caused by high-energy particles, we shall consider 10^{32} protons/sec, 10^{32} electrons/sec, and 1.4×10^{31} alpha particles/sec interacting over an area of 10^{19} cm^2 and through a depth of 10^9 cm. Isotropic production of gamma-ray photons will be assumed.

In all cases the gamma-ray flux at the earth in photons/cm^2 sec will equal the total gamma-ray production at the sun per second divided by $4\pi L^2 = 2.7 \times 10^{27}$ cm^2, where L is the astronomical unit.

V. Intensity and Spectrum of Gamma Radiation from the Sun

Let us now consider the gamma-ray production mechanisms proposed in Section II.

(1) Synchrotron radiation

The electromagnetic radiation by an electron of total energy E in a magnetic field B has an intensity maximum at the frequency ν_m, where

$$\nu_m = 1.26 \times 10^6 \, B_\perp \left(\frac{E}{M_0 c^2}\right)^2 \sec^{-1} \; ; \qquad (24)$$

and $B_\perp$ is the component of the magnetic field in gauss perpendicular to the particle velocity. For gamma-ray emission by this process,

$$\nu_m > 2.42 \times 10^{18} \sec^{-1} ,$$

and therefore, if we take $B_\perp = 10^3$ gauss,

$$E_{electron} > 22 \text{ Bev} .$$

Even with an exponential rigidity spectrum of $R_0 = 200$ Mv and $N_0 = 5 \times 10^{29}$ electrons/sec Mv, the flux at the earth of ~ 10 kev photons would be negligible. Results from bremsstrahlung radiation calculations indicate that R_0 is much less than 70 Mv for electrons. Therefore, synchrotron radiation is not an important mechanism for gamma radiation.

(2) Electron recombination with atoms (free-bound transitions)

The limit of the K series X-ray lines is a monotonically increasing function of Z, the atomic number of the atom. The highest Z of an atom of significant abundance in the corona is that of iron, Z = 26, whose K series limit lies at 1.3 angstroms (7 kev). When we consider that atoms of higher Z have very small abundances in the corona and that few of these atoms are ionized to the K shell, it is evident that line radiation resulting from transitions within atoms (bound-bound transitions) cannot produce gamma radiation.

The energy of a photon emitted in a free-bound transition is equal to the sum of the kinetic energy of the electron plus the ionization energy of the atom. Therefore emission is possible below the wavelengths corresponding to the ionization potential. Even in the corona, however, with an electron kinetic temperature of 10^6 °K, iron is not ionized to the K shell. It exists in several ionization states, but the abundance of Fe XX and more highly ionized ferric ions is negligible. Recombination with these ions could produce gamma radiation only if the captured electron were in the extreme high-velocity tail of the electron distribution. The scarcity of these electrons and the small capture cross section for such high velocities makes such a process a negligible one.

When we consider that higher Z elements have a drastically lower abundance than iron, and that they, too, are not ionized to the K shell, we see that gamma rays cannot be produced by free-bound recombinations in the corona. Lower Z elements, although more abundant, require electrons with even higher energies to produce gamma radiation, allowing us to neglect them also. Since flare temperatures are lower than coronal temperatures, free-bound collisions can be neglected as producers of gamma radiation.

(3) Decay of naturally radioactive nuclei

We can also eliminate naturally-occuring radioactive isotopes as sources of solar gamma radiation. The primary source of this type on the sun is potassium-40 (K^{40}). It has a half-life of 1.25×10^9 years, a terrestrial abundance of 0.01 per cent of all potassium, and decays by β^- emission accompanied by a 1.46 Mev gamma ray. Even if all solar potassium were in this isotopic form, the low abundance and long half-life would lead to infinitesimal fluxes at the earth. Isotopes with half-lives of less than 10^5 years would have disappeared from the outer regions of the sun, since the sun is at least 10^9 years old and no mixing occurs between the core, where new isotopes are produced, and the outer layers.

We shall consider the production of radioactive nuclei by reactions of the outer layers of the sun with energetic flare and cosmic-ray protons and alpha particles in the section on nucleon-nucleon reactions.

(4) Inverse Compton effect

The inverse Compton effect consists of the transfer of energy from energetic particles to photons by means of collisions between the two. The average energy loss, ΔE, of a particle of total energy E in such a collision with a photon of initial energy k, measured in the observer's rest frame, is [Feenberg and Primakoff, 1948; Donahue, 1948]

$$\Delta E = \gamma k'/[1 + k'/M_0c^2] \quad , \tag{25}$$

where

$$k' = \gamma k\,(1 + \beta \cos\theta);$$

$$\beta = v/c;$$

v = velocity of the particle;

$$\gamma = E/M_0c^2\ ;$$

M_0c^2 = rest energy of the particle;

$(\pi-\theta)$ = angle between the velocity vector of the particle and the velocity vector of the photon before collision.

The equation for the energy loss by the electron assumes

$$k' < \tfrac{1}{2} M_0c^2 \quad . \tag{26}$$

With $\beta \approx 1$ and the average value of $\beta \cos\theta$ equal to zero, the equation for ΔE becomes

$$\Delta E \approx \gamma^2 k \quad . \tag{27}$$

The average energy of the photons emitted by the sun is 1.4 ev; therefore, to transfer 10 kev to a thermal photon, electrons of approximately 43 Mev kinetic energy or protons of 80 Bev kinetic energy are necessary. Over the visible range (3000 to 6000 A) the energy emitted by the sun is 7.4×10^{10} ergs/cm^2 sec; during a flare this value might become 1.1 times as great [Parker, 1957]. Therefore the photon density at the sun is approximately 10^{12} cm^{-3}. With a solar constant of 1.94 cal/cm^2 min, and an average thermal photon energy of 1.4 ev, the photon density at the earth is about 2×10^7 cm^{-3}.

Making use of the method of Feenberg and Primakoff [1948], we find the number of Compton collisions with thermal solar photons made by an electron traveling radially from the sun to the earth is 8.7×10^{-2}. A proton would make only 2.6×10^{-8} collisions.

The integral gamma-ray flux at the earth is then calculated by considering the total number of electrons for a given rigidity spectrum with energy greater than 50 Mev incident per second on the high photon-density region near the sun, where most of the collisions occur. The integral flux of photons at the earth with energy greater than 10 kev is given in Table 7.

As Table 7 shows, for R_0 greater than 5 Mv the flux at the earth is detectable. Bremsstrahlung calculations, however, indicate that R_0 for electrons is much less than 5 Mv. It must also be pointed out that since both inverse Compton and bremstrahlung gamma rays have a continuous energy spectrum, the former will be masked by the latter unless the electron R_0 is greater than 10 Mv. Since this does not seem to be the case, the inverse Compton effect is not an important gamma-ray source.

Stein and Ney [1963] have proposed that the white light produced by some flares is caused by synchrotron radiation of electrons with $R_0 = 200$ Mv. If such electrons exist in a flare, a detectable gamma-ray flux at the earth resulting from the inverse Compton effect is possible [Gordon, 1960].

(5) Electron bremsstrahlung

A mechanism that can produce a continuous spectrum of solar gamma radiation is electron bremsstrahlung. Bremsstrahlung can be considered the result both of free-free electron transitions caused by deceleration of high-energy electrons in the dense flare volume ($N \sim 3 \times 10^{13}$ cm^{-3}) and of free-free transitions by electrons in a hot gas (thermal bremsstrahlung).

Bremsstrahlung by high-energy electrons appears to be predominant. The quantum mechanical expression for the energy radiated per unit path length in the frequency range ν to $\nu + d\nu$ by a particle of rest mass M_0 in the field of a particle of charge Z is [Evans, 1955]

$$dW = N_Z \sigma_0 Z^2 (T + M_0 c^2) \bar{B}_{\nu \to \nu + d\nu} \frac{d(h\nu)}{T} \text{ ergs cm}^{-1} \quad , \qquad (31)$$

where

$$\sigma_0 = \frac{1}{137} (e^2/M_0 c^2)^2 = 0.580 \times 10^{-27} \text{ cm}^2 \quad ;$$

N_Z = number of particles of charge Z per cm^3;

T = kinetic energy of the particle;

$\bar{B}_{\nu \to \nu + d\nu}$ = the average value of a slowly varying function in the frequency interval ν to $\nu + d\nu$ [Bethe and Heitler, 1934].

Thus per unit path length the mean number of photons in the energy interval between $h\nu$ and $h\nu + d(h\nu)$ emitted per electron is $dW/h\nu$. The gamma-ray flux will be based on 10^{32} electrons/sec passing through the flare volume (10^{19} cm^2 $\times$ 10^9 cm) with a spectrum given by

$$\frac{dN}{dR} = N_0 e^{-R/R_0} \quad , \qquad \text{electrons/sec volt} \quad (32)$$

where

$$N_0 R_0 = 10^{32} \qquad \text{electrons/sec}$$

and R is related to the kinetic energy T by

$$R = \frac{1}{Z}\left[(T + M_0c^2)^2 - (M_0c^2)^2\right]^{\frac{1}{2}} . \qquad (33)$$

In the flare volume $N_Z = 3 \times 10^{13}$ cm^{-3}, and the average value of Z^2 is 1.36

The number of gamma-ray photons per cm^2 per sec in the frequency interval between ν and $\nu + d\nu$ at the earth is given by

$$dN_\gamma = \left[\int_R \left(\frac{dW}{h\nu}\frac{dN}{dR}\right) dR \, (10^9)\right] \Big/ \, 2.7 \times 10^{27} \ cm^{-2} \ sec^{-1} . \qquad (34)$$

We evaluated this integral numerically. The integral photon flux at the earth for a range of values of R_0 is given in Table 8 and Table 9.

In a region where the density is 3×10^{13} protons cm^{-3}, the electron spectrum is modified in seconds because of energy losses by synchrotron radiation and collisions in addition to bremsstrahlung. Stein and Ney [1963] give a comparison of the relative rate of energy loss. An accurate determination of the spectrum as a function of time is very difficult. The few gamma-ray spectra that are available [Friedman, 1963] indicate that the electron rigidity spectra have exponential decay constants, R_0, of less than 1 Mv.

Because of the lower densities in the chromosphere and corona regions outside of the flare volume, bremsstrahlung in these regions resulting from deceleration of high-energy electrons is negligible compared to bremsstrahlung in the flare volume.

Proton bremsstrahlung can be neglected compared to electron bremsstrahlung, since $\sigma_0 \sim 1/M_0^2$.

The intensity of the radiation from free-free electron transitions in a gas is given [Elwert, 1961; Stein and Ney, 1963] by

$$I = \frac{16}{3}\left(\frac{\pi}{6}\right)^{\frac{1}{2}}\left(\frac{e^2}{M_0c^2}\right)^2 (Ze)^2\left(\frac{M_0c^2}{kT}\right)^{\frac{1}{2}}$$

$$\times\ g e^{-h\nu/kT} N_e N_i \tag{35}$$

$$= 5.44 \times 10^{-39} Z^2 e^{-h\nu/kT}\left(\frac{1}{T^{\frac{1}{2}}}\right) N_e N_i \ \text{erg/cm}^3 \text{ sec ster cps},$$

where $Z^2 = 1.36$;

M_0 = electron mass;

k = Boltzmann's constant

= 8.616×10^{-5} ev/deg;

g = Gaunt factor ≈ 1;

T = temperature of gas, measured in degrees Kelvin;

N_e = electron density;

N_i = proton density.

For emission over 4π steradians from a volume of 10^{28} cm^3, where $N_e = N_i = 3 \times 10^{13}$ cm^{-3}, the integral gamma-ray flux at the earth is given by

$$I_{earth} = \frac{3.1 \times 10^{-10}}{T^{\frac{1}{2}}} \int_{10\ kev}^{\infty} e^{-h\nu/kT}\ d\nu\ \frac{erg}{cm^2\ sec}$$

$$= 6.5 \left(T^{\frac{1}{2}}\right) e^{-\frac{1.2 \times 10^8}{T}} \frac{erg}{cm^2\ sec} \quad . \qquad (36)$$

For temperatures of 10^5 or 10^6 °K, the flux at the earth is negligible. The observed value of the flux for the 8/31/59 flare for $h\nu > 20$ kev was 4.5×10^{-6} ergs/cm^2 sec [Chubb, Friedman, and Kreplin, 1960] . Temperatures of the order of 10^7 °K or higher could generate the observed flux. A gas at these temperatures, however, would not radiate in H_α and thus we cannot assume that the volume of the region emitting gamma rays is the same as that emitting H_α . Although the duration of the 8/31/59 flare was of the order of minutes, other observed gamma-ray bursts occurred in seconds. Such rapid changes in the flux also rule out thermal origin from a large volume. At energies less than 10 kev, bremsstrahlung by thermal electrons may be the most important source of X-rays [Kawabata, 1960; de Jager, 1963; Friedman, 1963] .

(6) Nucleon-nucleon reactions

(a) Thermonuclear reactions. The kinetic temperature of flares and the corona is high enough so that thermonuclear reactions may occur. The energy liberated by mass conversion in these reactions can be in the form of gamma radiation or positrons which annihilate to form gamma radiation. The thermonuclear reactions most likely to produce gamma radiation, considering relative abundances and Coulomb barrier potentials, are

$$\text{(A)}\quad H^1 + H^1 \rightarrow H^2 + e^+ + \nu$$

$$e^+ + e^- \rightarrow 2\gamma \ (E_\gamma = 0.51 \text{ Mev}),$$

$$\text{(B)}\quad H^1 + n^1 \rightarrow H^2 + \gamma \ (E_\gamma = 2.23 \text{ Mev}),$$

$$\text{(C)}\quad H^1 + H^2 \rightarrow He^3 + \gamma \ (E_\gamma = 5.5 \text{ Mev}).$$

The reaction rate between two unlike particles is given by

$$r = n_1 n_2 < \sigma v > , \qquad \text{cm}^{-3} \text{ sec}^{-1} \quad (37)$$

where n_1 and n_2 are the number of reacting particles per cm^3 and $< \sigma v >$ is the average of the product of the reaction cross section and the relative velocity of the reacting particles. For reactions between like particles,

$$r = \frac{n^2}{2} < \sigma v > \quad . \qquad \text{cm}^{-3} \text{ sec}^{-1} \quad (38)$$

If the particles have a Maxwell-Boltzmann velocity distribution, then [Gamow and Critchfield, 1949; Cameron, 1961; Salpeter, 1952]

$$r = \frac{7.25 \, n_1 \, n_2}{Z_1 \, Z_2 \, A_1 \, A_2} \, (10^{-22}) \, (A_1 + A_2) \, S \, \tau^2 e^{-\tau} \, , \qquad \text{cm}^{-3} \text{ sec}^{-1} \quad (39)$$

where

$$\tau = 42.48 \left[\frac{Z_1^{\,2} Z_2^{\,2} A_1 \, A_2}{A_1 + A_2} \right]^{1/3} T_6^{\,1/3} \quad ;$$

$$S = \sigma \, E \exp \left\{ 988 \, Z_1 \, Z_2 \left[\frac{A_1 \, A_2}{(A_1 + A_2) E} \right]^{\frac{1}{2}} \right\} \text{ ev barn;}$$

Z = atomic number;

A = atomic mass number;

T_6 = temperature in units of 10^6 °K;

E = energy corresponding to the relative velocity $v = \frac{1}{2} m v^2$;

m = reduced mass = $m_1 m_2/(m_1 + m_2)$;

σ = cross section for the reaction in barns (10^{-24} cm^2) at the energy E.

S is a slowly varying function of the energy E and can be considered constant.

For reaction (A) the value of S is 3.12×10^{-19} ev barn [Salpeter, 1952] . The reaction rates and gamma-ray fluxes at the earth are given in Table 10. If we take the volume of the flare to be 10^{28} cm^3, the gamma-ray flux at 0.51 Mev is 3×10^{-30} photons/cm^2 sec at the earth. In these calculations the positrons were assumed to annihilate instantaneously. We will discuss the positron-annihilation time in a later section. For a corona volume of 6.2×10^{32} cm^3 (a hemispherical shell whose outer radius is 1.2 solar radii), a temperature of 1.5×10^6 °K, and a density of 10^9 cm^{-3}, the gamma-ray flux at the earth is 7×10^{-28} photons/cm^2 sec. For a coronal condensation volume of 1.2×10^{30} cm^3 (1.2×10^{22} cm^2 $\times 10^8$ cm), a temperature of 4×10^6 °K, and a density of 5×10^{10} cm^{-3}, the flux at the earth is 1.4×10^{-25} photons/cm^2 sec.

In reaction (B), neutron capture by a proton to form deuterium, the reaction rate is given by

$$r = n_n n_p \langle \sigma v \rangle \qquad \mathrm{cm}^{-3}\ \mathrm{sec} \quad (40)$$

and

$$\sigma = \frac{7.30 \times 10^{-20}}{v} , \qquad \mathrm{cm}^2 \quad (41)$$

where n_n and n_p are the neutron and proton densities (cm^{-3}). In the flare volume $n_p = 3 \times 10^{13}\ \mathrm{cm}^{-3}$; consequently,

$$r = (2.2 \times 10^{-6})\ n_n \ . \qquad \mathrm{cm}^{-3}\ \mathrm{sec}^{-1} \quad (42)$$

The gamma-ray flux at the earth is then

$$I = (8.1 \times 10^{-6})\ n_n \ . \qquad \mathrm{photons/cm}^2\ \mathrm{sec} \quad (43)$$

Neutrons, with a half-life in the free state of 13 minutes, are not normally present at the solar surface. The neutrons originate from nuclear reactions of flare-accelerated protons and alpha particles with nuclei present in the flare region, primarily

$$He^4\ (p, pn)\ He^3 \ ,$$

and from thermonuclear reactions, primarily

$$H^2\ (d, n)\ He^3$$
$$H^3\ (d, n)\ He^4 \ .$$

Consideration of all (p, n), (p, pn), (p, 2n), (α, n), (α, np), and (α, 2n) reactions with helium, carbon, and oxygen (see 6b) gives a neutron production rate of 0.1 cm^{-3} sec^{-1} for R_0 = 70 Mv and 0.7 cm^{-3} sec^{-1} for R_0 = 200 Mv. The mean neutron energy is a few Mev.

Post [1956] has discussed the thermonuclear reactions, and has calculated the reaction rate for a flare. For a deuteron density $n_d \approx 10^{-5} n_p$, $n_p = 3 \times 10^{13}$ cm^{-3}, and a temperature of 3.5×10^5 °K, the neutron production rate from the d-d reaction is negligible.

Most of the neutrons produced in these reactions will escape from the flare region. Neutrons with an energy of 3 Mev have a velocity approximately equal to 3×10^9 cm/sec. The total cross section for n-p reactions at this energy is ~ 3 barns; thus, for $n_p \doteq 3 \times 10^{13}$ cm^{-3}, the neutron mean free path is $\sim 10^{10}$ cm .

Because of the absence of neutrons in the corona and the low production of neutrons in this region during a flare, the gamma-ray flux from the entire corona caused by reaction (B) is negligible compared to production in the flare volume.

Although reaction (B) produces deuterium in the region of the flare, it is interesting to note that it would be in quantities far below that spectroscopically detectable. The only claim to have observed deuterium in a flare was based on an unsymmetrical H_α line (the D_α line being shifted 1.78 angstroms from the H_α line) [Goldberg, Mohler, and Müller, 1958] . The deuterium abundance derived was from 1 to 4 per cent that of the hydrogen abundance, which compares with a normal abundance of less than 4×10^{-5} that of hydrogen [Righini, 1962] . The line asymmetry, never seen in any other flare, was probably caused by mass motions in the line of sight.

The reaction (C), involving deuterium as a reagent, is also a poor gamma-ray producer. The value of S for this reaction is 7.8×10^{-2} ev barn [Cameron, 1957]. Even assuming the deuterium abundance to be 18 per cent that of hydrogen in a flare, a flux at the earth of only 1×10^{-16} photons/cm^2 sec is obtained from this reaction. With an abundance of deuterium in the corona less than 4×10^{-5} that of hydrogen, the flux at the earth from this reaction would be less than 9.5×10^{-14} photons/cm^2 sec from the entire corona. For a coronal condensation at 4×10^6 °K, the flux would be less than 1.8×10^{-10} photons/cm^2 sec.

(b) De-excitation of nuclei produced by nuclear reactions. Table 11 lists the proton-induced nuclear reactions of interest to this investigation, either because they produce gamma radiation directly, or because they produce it indirectly by positron formation, or because they produce neutrons.

The number of nuclear reactions per second, r, in the flare volume is given by

$$r = \int_{R_t}^{\infty} n_t \, \sigma_r \, \ell \, \frac{dN}{dR} \, dR \quad , \qquad \text{sec}^{-1} \quad (44)$$

where

n_t = density of target nuclei (cm^{-3});

σ_r = reaction cross section (cm^2);

ℓ = interaction path length, which is equal to the flare thickness (cm);

$\frac{dN}{dR}$ = number of particles incident on the flare volume per second per volt;

R_t = rigidity at threshold for the reaction.

Calculations of the reaction rate assume that the accelerated particles pass through the flare volume (10^{19} cm^2 x 10^9 cm) and interact over a distance of 10^9 cm. The target nuclei densities are given in Table 6. We take the proton flux to be 10^{32} protons/sec over the flare area and assume an exponential rigidity spectrum (Section IV).

The reaction cross section can be written as the sum of the cross sections of individual inelastic reactions. In the energy range of interest, for proton reactions with a given target nucleus

$$\sigma_r = \sigma\,(p, p') + \sigma\,(p, n) + \sigma\,(p, pn) + \sigma\,(p, 2p)$$

$$+ \sigma\,(p, 2n) + \sigma\,(p, \alpha) + \ldots, \tag{45}$$

where we have neglected higher-order terms as well as the reactions (p, γ) and (p, d).

Using the optical model assumptions of Fernbach, Serber, and Taylor [1949] for a uniform density nucleus of radius $\rho = \rho_0 A^{1/3}$, we can approximate the reaction cross section [Wattenburg, 1957] by

$$\sigma_r = \pi\rho^2 \left[1 - \frac{1-(1+2K\rho)\, e^{-2K\rho}}{2K^2\rho^2} \right], \tag{46}$$

where $\quad K = 5 \times 10^{12}, \quad \text{cm}^{-1}$

and $\quad \rho_0 = (1.28 \pm 0.3) \times 10^{-13} \quad \text{cm}$

over the energy region where σ_r is approximately constant.

Direct gamma-ray emission results from these reactions because of decay of the excited states of the product nuclei. This decay usually occurs in less than 10^{-10} second. This gamma-ray production rate in the flare is given by the product of the reaction rate, r, and the gamma-ray multiplicity per reaction, m. Table 12 gives the value of $\sigma_r m$ as a function of energy for flare-accelerated protons interacting with helium, carbon, nitrogen, and oxygen. From the threshold energy of a few Mev to about 30 Mev, the predominant gamma-ray emission results from (p, p′) reactions (inelastic scattering) on carbon [Burge, 1959], nitrogen [Oda et al., 1960], and oxygen [Kobayashi, 1960]. A multiplicity, m, of one was used for carbon, and a multiplicity of two was used for nitrogen and oxygen in this energy range [Scherrer, Theus, and Faust, 1953; Hofmann and Winckler, 1963]. The gamma-ray production rate decreases at higher energies although σ_r is constant, implying that in most reactions the end-product nucleus is produced in its ground state. For proton energies greater than 30 Mev, the value of $\sigma_r m$ measured at 150 Mev [Foley, Solmon, and Clegg, 1962; Clegg, Foley, Solmon, and Segel, 1961] was used.

The gamma-ray emission caused by these reactions consists of line emission in the energy region from 0.5 to 10 Mev. For example, the predominant line emission from carbon is 4.43 Mev and from oxygen, 6.15 Mev. Over this energy region the gamma-ray flux at the earth for $R_0 = 70$ Mv is 0.16 photon/cm^2 sec and for $R_0 = 200$ Mv is 0.24 photon/cm^2 sec.

Assuming a ratio of α particles to protons of 0.14 for the accelerated particles, and acceleration to the same rigidity spectrum, we can neglect α-particle reactions.

Because of the drastically reduced target densities in the corona, nuclear-reaction rates there can be neglected in comparison with reaction rates in the flare itself.

The gamma-ray fluxes predicted for this energy region are certainly detectable; little effort has been made, however, to investigate this portion of the spectrum.

(c) π^0-meson decay. At proton energies above 200 Mev the predominant mechanism of gamma-ray production is the decay of π^0 mesons,

$$\pi^0 \to 2\gamma \quad ,$$

which are produced in proton-proton collisions. The decay time for the π^0 meson is 2×10^{-16} second. For decay at rest each of the photons would have an energy of 70 Mev.

The cross section as a function of proton and α-particle energy for the reactions

$$\left.\begin{matrix}\alpha \\ p\end{matrix}\right\} + p \to \left.\begin{matrix}\alpha \\ p\end{matrix}\right\} + p + \pi^0$$

and also reactions for multiple meson production are given by Pollack and Fazio [1963] . We computed the gamma-ray flux at the earth as in section (b), using exponential rigidity spectra with $R_0 = 70$ Mv and $R_0 = 200$ Mv. For $R_0 = 70$ Mv the flux ($h\nu > 50$ Mev) at the earth is 4.8×10^{-6} photons/cm^2 sec, and for $R_0 = 200$ Mv the flux is 7.4×10^{-2} photons/cm^2 sec. Note that the gamma-ray flux in this energy region is highly dependent on the value of R_0 and certainly indicates the presence of very high-energy particles in the flare. Neutral meson decay is the chief source of radiation for all energies above 50 Mev.

It is interesting to note that π^0 mesons can also be produced by galactic cosmic-ray protons and α particles interacting at the solar surface. The flux at the earth for photons with energy greater than 50 Mev caused by this effect is $\sim 10^{-6}$ photons/cm^2 sec.

(7) Positron-electron annihilation.

Positrons generated as by-products of nuclear reactions on the sun can annihilate with electrons to form gamma radiation:

$$e^+ + e^- \rightarrow 2\gamma \quad ,$$

where the gamma-ray energy is 0.51 Mev for annihilation at rest. The cross section for this reaction has a maximum when the positron total energy, E_+ , approximately equals the positron rest mass energy, $M_0c^2 = 0.51$ Mev. At this energy the annihilation rate, r, is given by

$$r = n_+ n_- (\pi r_0^2) c \ , \qquad \text{cm}^{-3}\ \text{sec}^{-1} \quad (47)$$

where n_+ and n_- = the positron and electron densities (cm^{-3});

$$\pi r_0^2 = 0.25 \times 10^{-24}; \qquad \text{cm}^2$$

c = velocity of light.

Positrons are generated by the beta-decay of nuclei and the decay of π^+ mesons.

(a) Beta-decay of nuclei. The nucleon-nucleon reactions discussed above, in addition to producing nuclei in excited states, also produce nuclei which are radioactive and decay by positron emission. The gamma-ray flux resulting from the subsequent positron annihilation depends not only on the rate of production of the radioactive nuclei but also on the mean lifetime for decay. The only nuclei which can contribute significantly to the gamma-ray flux are those that decay with a mean lifetime less than or approximately equal to the total time, t_0, that the accelerated protons interact with the flare. The rate of decay at time t after the protons initially interact is given, for $t \leq t_0$, by

$$\Phi = r\,(1-e^{-\lambda t}) \quad , \qquad \text{sec}^{-1} \quad (48)$$

where r = constant rate of production of the radioactive nuclei;

λ = decay constant = $1/\tau$;

τ = mean lifetime.

At $t = t_0$ the production ceases and the rate of decay becomes, for $t > t_0$,

$$\Phi = re^{-\lambda(t-t_0)}(1-e^{-\lambda t_0}) \quad . \qquad \text{sec}^{-1} \quad (49)$$

For an interaction time t_0 = 100 seconds in a flare, the principal sources of positrons, based on reaction rates and decay times, for proton and α-particle-induced reactions are given in Table 13. The average cross sections assumed in Table 13 were calculated by Chupp [1963] and are estimated from compound nucleus formation cross sections by assuming all decay channels equally probable. The most important source of positrons is

$$C^{12}(p, n)\, N^{12}$$
$$N^{12}(B^{+})\, C^{12} \quad .$$

For this reaction the gamma-ray flux at the earth is 3.4×10^{-3} photons/cm^2 sec for R_0 = 70 Mv and 2.1×10^{-2} photons/cm^2 sec for R_0 = 200 Mv.

For these fluxes the positron was assumed to annihilate instantaneously. This is not the actual situation. The total time from production to annihilation is the sum of the time needed for the positron to lose energy by synchrotron radiation and ionization to a final total energy of ~ 0.5 Mev, plus the time for annihilation at this energy.

The rate of energy loss is given [Ginzburg, 1958] by

(1) magnetic bremsstrahlung,

$$dE/dt = -4 \times 10^{-15}\, E^2 B_\perp{}^2 = -bE^2 \text{ ev/sec} \; ; \qquad (50)$$

(2) collision in ionized hydrogen,

$$dE/dt = -7.62 \times 10^{-9}\, n(\ln \frac{E}{mc^2} - \ln n + 7.46) \text{ ev/sec} \qquad (51)$$

$$\approx -a \;, \qquad \text{ev/sec}$$

where E is the total energy of the positron; $B_\perp$ is the component of the magnetic field in gauss perpendicular to the motion; n is the proton density; mc^2 is the rest energy of the positron (0.511 Mev), and a and b are constants.

The total rate of energy loss is

$$dE/dt = -a-bE^2 \quad , \qquad \text{ev/sec} \quad (52)$$

where

$$a = 10^7 \; ;$$

$$b = 10^{-9} \; ;$$

$$B_\perp^2 = 2.5 \times 10^5 \text{ gauss}^2 \; ;$$

$$n = 3 \times 10^{13} \text{ cm}^{-3} \; .$$

Solving the above equation for t, we have

$$t = \frac{\tan^{-1}\left[(b/a)^{\frac{1}{2}} E_0\right] - \tan^{-1}\left[(b/a)^{\frac{1}{2}} E\right]}{(ab)^{\frac{1}{2}}} \; ,$$

where

$$E = E_0 \text{ at } t = 0 \; .$$

For $E_0 = 10$ Mev and $E = 0.5$ Mev, $t \approx 1$ sec .

The annihilation time is

$$t_a = 1/n_- \pi r_0^2 c \approx 4 \text{ sec}$$

for

$$n_- = 3 \times 10^{13} \text{ cm}^{-3} \; .$$

Therefore, the total time from production to annihilation is approximately 5 seconds.

(b) Meson decay. An additional source of positrons is the decay of π^+ mesons produced in proton-proton and proton-α-particle reactions:

$$\left.\begin{matrix} p \\ \alpha \end{matrix}\right\} + p \rightarrow \pi^+ + n + \left\{\begin{matrix} p \\ \alpha \end{matrix}\right.$$

$$\pi^+ \rightarrow u^+ + \nu \qquad (\tau = 2.6 \times 10^{-8} \text{ sec})$$

$$u^+ \rightarrow e^+ + \nu + \bar{\nu} \quad . \qquad (\tau = 2.2 \times 10^{-6} \text{ sec})$$

The threshold for the p-p reaction is 290 Mev and for the p-α reaction, 172 Mev. Multiple meson production is possible at higher energies. The production of π mesons, including cross sections and multiplicities, was previously considered by Pollack and Fazio [1963]. Note that just above threshold energy to approximately 1 Bev, the production of π^+ mesons dominates the production of π^0 mesons.

For a typical positron energy of 100 Mev, the time from production to annihilation is about 8 seconds.

The gamma-ray flux at the earth produced by positrons from beta-decay and meson decay is given in Table 14 for two values of R_0 : R_0 = 70 Mv and R_0 = 200 Mv.

VI. Modification of Calculated Fluxes

Because of the wide variations in the parameters involved in the calculation of gamma-ray fluxes from solar flares, all calculations in this paper are based on simple representative values. Fortunately, most of the results are directly proportional to the parameters which change from flare to flare, and can easily be converted to any observed set of parameters for a given flare. The most important parameters are the area of the flare; the number of protons, electrons, and alpha particles interacting in the flare per second; and the exponential decay constant, R_0, of the particle spectrum. Only the last of the three parameters requires any amount of recalculation other than multiplication, and in this case the photon fluxes have been calculated for a range of values of R_0 .

Such other quantities as the density of the atomic species and the path length of particles through the flare may also change in value from flare to flare. Since these quantities are difficult to determine for any one flare, it is probably best to use the values available for an average flare.

VII. Summary

The gamma-ray spectrum of the sun is simple in its qualitative aspects and can yield valuable information on the nature of solar flares. Almost all gamma-ray activity will be associated with a flare region. The spectrum from 10 kev to a few Mev consists of continuous radiation, caused primarily by electron bremsstrahlung, which monotonically decreases in intensity with increasing energy. Line emission occurs at 0.51 kev because of positron annihilation; at 2.23 Mev, because of deuteron formation; and throughout the spectrum from 0.5 to 10 Mev because of nuclear de-excitation. The most important line emissions caused by the de-excitation process are at 4.43 Mev, from C^{14}, and at 6.14 Mev, from O^{16}.

All the above sources of line emission indicate the occurrence of nuclear reactions during a flare. The intensity of the 2.23 Mev line is a measure of the neutron density in a flare. The gamma-ray flux above 50 Mev is primarily caused by π^0-meson decay, which produces a continuous spectrum peaking at about 100 Mev. The flux in this energy region is very sensitive to the value of R_0 and can yield much information about the accelerated particle spectrum in the flare. In discussing the detectability of line emission, we must remember that the strength of the continuum background radiation in relation to the line intensity determines just how easily the line may be detected. The 0.51 Mev line will be in the bremsstrahlung continuum and will therefore be difficult to detect. The 2.23 Mev line and the line emission caused by nuclear de-excitation are relatively free of this background. The deuteron line may be difficult to detect, depending on the neutron density; the de-excitation gamma rays should, however, be easily detectable in a large flare. At present little effort has been made to search for these lines.

Almost all solar gamma radiation is caused by flares. The only radiation that should emanate from a completely quiet sun is that resulting from the interaction of galactic cosmic rays with the solar photosphere. The occurrence, even during quiet periods, of many class 1- flares and sub-flares, however, may result in small, irregular fluxes of gamma radiation.

The present status of the detection of X-rays and gamma rays from the sun has been summarized by Friedman [1963]. The highest-energy photons detected were in the 300 to 500 kev region [Peterson and Winckler, 1959], and all gamma rays detected thus far give spectra indicative of electron bremsstrahlung. All of the radiation has occurred in bursts associated with flares. Present upper limits on other portions of the spectrum are given by the results of experiments aboard the first Orbiting Solar Observatory [Lindsay, 1963]. The sensitivity of present detectors in the 0.1 to 3.0 Mev energy region is about 1 photon/cm^2 sec and above the 50 Mev region, $\sim 10^{-3}$ photon/cm^2 sec. No experiments have so far been performed in the 3.0 to 50 Mev region.

The only indication of nuclear reactions in a solar flare has been the detection of H^3 and He^3 in the exposed section of a satellite (Discoverer 17) during a class 3+ flare on November 12, 1960 [Fireman, DeFelice, and Tilles, 1961; Schaeffer and Zähringer, 1962; Hamm, Lingenfelter, MacDonald, and Libbey, 1962]. Both H^3 and He^3 could be produced by the reactions

$$He^4 \ (p, d) \ He^3$$

$$He^4 \ (p, pn) \ He^3$$

$$He^4 \ (p, 2p) \ H^3 \quad .$$

To better understand the processes occurring during a solar flare we must investigate the gamma-ray portion of the electromagnetic spectrum emitted by a flare. Because of local background radiation, the construction of sensitive, directional detectors is not easy but is worth pursuing. Space vehicles such as the Orbiting Solar Observatories are available to carry gamma-ray detectors, and we urge that experiments be planned for the coming maximum of the solar cycle to thoroughly investigate this portion of the spectrum.

We thank Dr. A. G. W. Cameron, Prof. E. L. Chupp, and Dr. H. Mitler for their assistance and suggestions.

References

Aller, L. H., The abundances of the elements in the sun and stars, in Handbuch der Physik, edited by S. Flügge, Springer-Verlag, Berlin, 51, 324-352, 1958.

Beckers, J. M., A search for white light flares, Observatory, 82, 66-68, 1962.

Bethe, H., and W. Heitler, Stopping of fast particles and creation of electron pairs, Proc. Roy. Soc., A, 146, 83-112, 1934.

Burge, E. J., The total proton reaction cross section of carbon from 10-68 Mev by a new method, Nuclear Physics, 13, 511-515, 1959.

Cameron, A. G. W., Stellar evolution, nuclear astrophysics and nucleogenesis, AECL No. 454, Atomic Energy of Canada, Ltd., Chalk River Project, Chalk River, Ontario, 1961.

Chubb, T. A., H. Friedman, and R. W. Kreplin, Measurements made of high-energy x-rays accompanying three class 2^+ solar flares, J. Geophys. Res., 65, 1831-1832, 1960.

Chupp, E. L., private communication, 1963.

Clegg, A. B., K. J. Foley, G. L. Salmon, and R. E. Segel, Gamma radiation from the medium energy proton bombardment of lithium, beryllium, boron, carbon and nitrogen, Proc. Phys. Soc. (London), 78, 681-694, 1961.

Donahue, T. M., The significance of the absence of primary electrons for theories of the origin of the cosmic radiation, Phys. Rev., 84, 972-980, 1951.

Elwert, G., Theory of x-ray emission of the sun, J. Geophys. Res., 66, 391-401, 1961.

Evans, R. D., The Atomic Nucleus, McGraw-Hill Book Company, Inc., New York, 972 pp., 1955.

Feenberg, E., and H. Primakoff, Interaction of cosmic-ray primaries with sunlight and starlight, Phys. Rev., 73, 449-469, 1948.

Fernbach, S., R. Serber, and T. B. Taylor, The scattering of high energy neutrons by nuclei, Phys. Rev., 75, 1352-1355, 1949.

Fireman, E. L., J. DeFelice, and D. Tilles, Solar flare tritium in a recovered satellite, Phys. Rev., 123, 1935-1936, 1961.

Flamm, E., R. E. Lingenfelter, G. J. MacDonald, and W. Libbey, Tritium and He^3 in solar flares and loss of helium from the earth's atmosphere, Science, 138, 48-49, 1962.

Foley, K. J., G. L. Salmon, and A. B. Clegg, Gamma radiation from the bombardment of ^{16}O and ^{19}F nuclei with 150 Mev protons, Nuclear Physics, 31, 43-52, 1962.

Freier, P. S., and W. R. Webber, Exponential rigidity spectrums for solar-flare cosmic rays, J. Geophys. Res., 68, 1605-1629, 1963.

Friedman, H., Ultraviolet and x rays from the sun, Ann. Rev. Astron. Astrophys., 1, 59-96, 1963.

Gamow, G., and C. L. Critchfield, Theory of Atomic Nucleus and Nuclear Energy-Sources, Clarendon Press, Oxford, 344 pp., 1949.

Ginzburg, V. L., The origin of cosmic radiation, in Progress in Elementary Particle and Cosmic Ray Physics, edited by J. G. Wilson and S. A. Wouthuysen, Interscience Publ., Inc., New York, IV, 339-421, 1958.

Goldberg, L., O. C. Mohler, E. A. Müller, The profile of Hα during the limb flare of February 10, 1956, Astrophys. J., 127, 302-307, 1958.

Goldberg, L., E. A. Müller, and L. H. Aller, The abundances of the elements in the solar atmosphere, Astrophys. J. Supplements, 5, no. 45, 1-138, 1960.

Gordon, I. M., The nature of γ-emission in solar flares and the formation of cosmic particles in active solar regions, Soviet Astron.—A J, 4, 873-875, 1961.

Hofmann, D. J., and J. R. Winckler, Simultaneous balloon observations at Fort Churchill and Minneapolis during the solar cosmic ray events of July 1961, J. Geophys. Res., 68, 2069-2098, 1963.

Van de Hulst, H. C., The chromosphere and the corona, in The Solar System, 1, edited by G. P. Kuiper, Univ. of Chicago Press, Chicago, 207-321, 1953.

de Jager, C., Structure and dynamics of the solar atmosphere, in Handbuch der Physik, edited by S. Flügge, Springer-Verlag, Berlin, 52, 80-362, 1959.

de Jager, C., A note on bursts of radio emission and high energy (> 20 kev) x-rays from solar flares, in Space Research III, edited by W. Priester, North-Holland Publ. Co., Amsterdam, 836-838, 1963.

Kaplan, I., Nuclear Physics, Addison-Wesley, Publ. Co., Inc., Cambridge, Mass., 609 pp., 1955.

Kawabata, K., The relationship between post-burst increases of solar microwave radiation and sudden ionospheric disturbances, Rep. Ionosph. Space Res. Japan, 14, 405-426, 1960.

Kobayashi, S., Elastic and inelastic scattering of protons by oxygen in the energy region of 6.9 Mev to 15.6 Mev, Journ. Phys. Soc. Japan, 15, 1164-1174, 1960.

Leighton, R. B., Observations of solar magnetic fields in plage regions, Astrophys. J., 130, 366-380, 1959.

Lindsay, J. C., Scientific results of the first orbiting solar observatory, Trans. Amer. Geophys. Union, 44, 722-725, 1963.

Meyer, P., and R. Vogt, High-energy electrons of solar origin, Phys. Rev. Letters, 8, 387-389, 1962.

Oda, Y., M. Takeda, N. Takano, T. Yamazaki, C. Hu, K. Kibuchi, S. Kobayashi, K. Matsuda, and Y. Nagahara, Elastic and inelastic scattering of protons from N, Ne, Mg, Si, S, and A in the energy range from 7.6 Mev to 14.2 Mev, Journ. Phys. Soc. Japan, 15, 760-761, 1960.

Parker, E. N., Acceleration of cosmic rays in solar flares, Phys. Rev., 107, 830-836, 1957.

Peterson, L., and J. R. Winckler, Short γ-ray burst from a solar flare, Phys. Rev. Letters, 1, 205-206, 1958.

Peterson, L. E., and J. R. Winckler, Gamma-ray burst from a solar flare, J. Geophys. Res., 64, 697-707, 1959.

Pollack, J. B., and G. G. Fazio, Production of π mesons and gamma radiation in the galaxy by cosmic rays, Phys. Rev., 131, 2684-2691, 1963.

Post, R. F., Controlled fusion research - an application of the physics of high temperature plasmas, Rev. Mod. Phys., 28, 338-362, 1956.

Righini, G., The abundance of isotopes in the solar atmosphere, Observatory, 82, 106-107, 1962.

Salpeter, E. E., Nuclear reactions in the stars. I. Proton-proton chain, Phys. Rev., 88, 547-553, 1952.

Schaeffer, O. A., and J. Zähringer, Solar flare helium in satellite materials, Phys. Rev. Letters, 8, 389-390, 1962.

Scherrer, V. E., R. B. Theus, and W. R. Faust, Gamma rays from interaction of 14-Mev neutrons with various materials, Phys. Rev., 91, 1476-1478, 1953.

Stein, W. A., and E. P. Ney, Continuum electromagnetic radiation from solar flares, J. Geophys. Res., 68, 65-81, 1963.

Thomas, R. N., and R. G. Athay, Physics of the Solar Chromosphere, Interscience Publ., Inc., New York, 422 pp., 1961.

Warwick, J. M., Heights of solar flares, Astrophys. J., 121, 376-384, 1955.

Wattenburg, A., Nuclear reactions at high energies, in Handbuch der Physik, edited by S. Flügge, Springer-Verlag, Berlin, 40, 450-537, 1957.

Zirin, H., Physical conditionsin limb flares and active prominences. II. A remarkable limb flare, December 18, 1956, Astrophys. J., 129, 414-423, 1959.

TABLE 1. PHOTOELECTRIC CROSS SECTION

Photon Energy (kev)	σ_{ph}/Z^5 (cm^2/atom)
10	1.34×10^{-26}
50	4.78×10^{-29}
100	4.24×10^{-30}
500	1.51×10^{-32}
1000	1.34×10^{-33}

TABLE 2. COMPTON TOTAL CROSS SECTION

Photon Energy (Mev)	σ_c/Z (10^{-25} cm^2/atom)
0.010	6.40
0.102	4.90
0.511	2.87
1.02	2.09
5.11	0.817
10.22	0.502
51.10	0.143

TABLE 3. PAIR PRODUCTION CROSS SECTION

Photon Energy (Mev)	σ_{pr}/Z^2 (10^{-27} cm^2/atom)
1.02	0
1.53	0.050
2.04	0.189
3.07	0.524
5.11	1.15
10.2	2.12
25.4	3.56

TABLE 4. PROPERTIES OF SOLAR CHROMOSPHERE AND CORONA

(A) Chromosphere

Height (km)	Temperature (^{o}K)	Atom Density (cm^{-3})
500	6250	6.2×10^{13}
750	--	9.9×10^{12}
1000	7500	1.15×10^{12}

(B) Corona

Height (km)	Temperature (^{o}K)	Proton Density (cm^{-3})
7.5×10^{3}	--	3.0×10^{9}
1.0×10^{4}	--	7.9×10^{8}
1.5×10^{4}	--	4.2×10^{8}
2.1×10^{4}	1.0×10^{6}	2.9×10^{8}
1.4×10^{5}	1.5×10^{6}	4.0×10^{7}
7.0×10^{5}	1.5×10^{6}	1.6×10^{6}
1.4×10^{6}	1.5×10^{6}	3.0×10^{5}

TABLE 5. PROPERTIES OF CHROMOSPHERIC FLARES

Class	Optical Duration (min.)	Relative Frequency	Mean Area on Disk (cm^2)
1-			2.2×10^{18}
1	4-43	0.72	4.8×10^{18}
2	10-40	0.25	1.0×10^{19}
3	20-155	0.03	2.9×10^{19}
3+	50-430		3.6×10^{19}

TABLE 6. RELATIVE SOLAR ABUNDANCES OF ELEMENTS

Element	Relative Abundance	Flare Density (cm^{-3})
H	1	3.0×10^{13}
He	0.14	4.2×10^{12}
C	5.2×10^{-4}	1.6×10^{10}
N	9.5×10^{-5}	2.8×10^{9}
O	9.1×10^{-4}	2.7×10^{10}

TABLE 7. INTEGRAL GAMMA-RAY FLUXES AT THE EARTH DUE TO INVERSE COMPTON EFFECT

R_0 (volts)	No. of Electrons ($E > 50$ Mev)	Photons/cm^2 sec ($E_\gamma > 10$ kev)
2.0×10^{8}	8.1×10^{31}	2.6×10^{3}
7.0×10^{7}	5.1×10^{31}	1.6×10^{3}
1.0×10^{7}	6.1×10^{29}	2.0×10^{1}
5.0×10^{6}	3.8×10^{27}	1.2×10^{-1}
8.0×10^{5}	7.1×10^{4}	2.3×10^{-24}

TABLE 8. INTEGRAL GAMMA-RAY FLUX (N_γ) AT THE EARTH DUE TO ELECTRON BREMSSTRAHLUNG

Photon Energy (E_γ)	N_γ (cm^{-2} sec^{-1}) > E_γ			
	$R_0 = 2 \times 10^8$ volts	$R_0 = 7 \times 10^7$ volts	$R_0 = 10^7$ volts	$R_0 = 5 \times 10^6$ vo
10 kev	172	150	116	105
20	162	141	105	93
30	150	129	91	77
40	132	123	85	70
50	140	118	80	65
100	126	105	65	51
200	113	91	51	37
300	105	83	43	30
400	99	77	37	25
500	94	73	34	22
1 Mev	81	59	23	13
5	51	31	5.9	1.8
10	39	22	2.2	0.37
50	16	4.8	1.3×10^{-2}	5.0×10^{-5}
100	8.0	1.5	6.8×10^{-5}	--
500	0.40	2.0×10^{-3}	--	--
1000	2.2×10^{-2}	1.6×10^{-6}	--	--

TABLE 9. INTEGRAL GAMMA-RAY FLUX (N_γ) AT THE EARTH DUE TO ELECTRON BREMSSTRAHLUNG

Photon Energy (E_γ)	N_γ (cm^{-2} sec^{-1}) $> E_\gamma$			
	$R_0 = 8 \times 10^5$ volts	$R_0 = 5 \times 10^5$ volts	$R_0' = 3.5 \times 10^5$ volts	$R_0 = 1.1 \times 10^5$ volts
10 kev	71	65	60	33
20	56	47	42	21
30	36	28	22	5.6
40	30	22	16	3.3
50	25	17	12	2.1
100	15	8.7	5.3	0.37
200	7.9	3.9	1.9	0.045
300	5.0	2.2	0.94	8.7×10^{-3}
400	3.4	1.3	0.53	2.2×10^{-3}
500	2.4	0.85	0.30	4.6×10^{-4}
600	1.7	0.56	0.18	1.7×10^{-4}
800	0.95	0.25	0.066	1.8×10^{-5}
1 Mev	0.57	0.12	0.025	9.1×10^{-7}
3	1.3×10^{-2}	6.0×10^{-4}	2.4×10^{-5}	--
5	1.0×10^{-3}	1.0×10^{-5}	9.1×10^{-8}	--

TABLE 10. $H^1 + H^1 \rightarrow H^2 + e^+ + \nu$ REACTION RATE

Solar Region	Temperature (^oK)	Proton Density (cm^{-3})	Reaction Rate ($cm^{-3}\ sec^{-1}$)
Flare	1×10^5	3×10^{13}	2.76×10^{-41}
	3.54×10^5	3×10^{13}	7.37×10^{-31}
Corona	8×10^5	2×10^8	1.97×10^{-36}
	8×10^5	10^9	4.93×10^{-35}
	1.5×10^6	2×10^8	1.27×10^{-33}
	1.5×10^6	10^9	3.18×10^{-32}
Coronal Condensation	2.5×10^6	5×10^{10}	5.14×10^{-27}
	4×10^6	5×10^{10}	1.38×10^{-25}

TABLE 11. ACCELERATED PROTON REACTIONS FOR THE PRODUCTION OF GAMMA RADIATION AND NEUTRONS

Reaction	Proton Threshold Kinetic Energy (Mev)
He^4 (p, pn) He^3	25.6
He^4 (p, 2pn) H^2	32.5
He^4 (p, 2p 2n) H^1	35.2
C^{12} (p, n) N^{12}	19.9
C^{12} (p, pn) C^{11}	20.3
C^{12} (p, 2p) B^{11}	16.7
N^{14} (p, n) O^{14}	6.4
N^{14} (p, pn) N^{13}	11.3
N^{14} (p, 2p) C^{13}	12.3
N^{14} (p, α) C^{11}	1.5
O^{16} (p, np) O^{15}	16.7
O^{16} (p, 2p) N^{15}	12.3
O^{16} (p, α) N^{13}	5.0

TABLE 12. CROSS SECTIONS FOR GAMMA-RAY PRODUCTION BY NUCLEAR DE-EXCITATION .

Target Nucleus	Flare Density (cm^{-3})	Energy Region (Mev)	$\sigma_r m$ (mb)
He^4	4.2×10^{12}	> 4	0
C^{12}	1.6×10^{10}	4-30 > 30	242 23
N^{14}	2.8×10^{9}	4-30 > 30	558 27
O^{16}	2.7×10^{10}	6-30 > 30	560 50

TABLE 13. PRINCIPAL SOURCES OF NUCLEI WHICH DECAY BY β^+ EMISSION

No.	Reaction	τ (sec)	Threshold Energy (Mev)	Average Cross Section (mb)	Nuclear Reaction Rate (10^{-4} cm^{-3} sec^{-1})	
					R_0 = 70 Mv	R_0 = 200 Mv
1.	C^{12} (p, n) N^{12} N^{12} (β^+) C^{12}	0.0125	19.9	46.0	5.6	30
2.	N^{14} (p, n) O^{14} O^{14} (β^+) N^{14}	72	6.4	53.3	3.4	8.8
3.	O^{16} (p, np) O^{15} O^{15} (β^+) N^{15}	124	16.7	52.9	16.2	60
4.	C^{12} (α, n) O^{15} O^{15} (β^+) N^{15}	124	11.4	22.7	0.26	1.86
5.	C^{12} (α, 2n) O^{14} O^{14} (β^+) N^{14}	72	29.0	30.3	0.13	1.80
6.	N^{14} (α, n) F^{17} F^{17} (β^+) O^{17}	66	6.1	0.6	1.7×10^{-3}	9.4×10^{-3}
7.	O^{16} (α, n) Ne^{19} Ne^{19} (β^+) F^{19}	17.7	15.2	26.3	1.1	3.2
8.	O^{16} (α, 2n) Ne^{18} Ne^{18} (β^+) F^{18}	1.6	29.6	33.7	0.24	3.2

TABLE 14. GAMMA-RAY FLUX AT THE EARTH DUE TO POSITRON ANNIHILATION

Source Reaction	Flux (Photons/cm^2 sec)	
	R_0 = 70 Mv	R_0 = 200 Mv
C^{12} (p, n) N^{12} N^{12} (β^+) C^{12}	3.4×10^{-3}	2.1×10^{-2}
$\pi^+ \rightarrow \mu^+ + \nu$ $\mu^+ \rightarrow e^+ + \nu + \bar{\nu}$	5.7×10^{-5}	4.2×10^{-1}